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MODELING OF ADAPTIVE OPTICS SYSTEMS AT RAYTHEON OPTICAL SYSTEMS INC

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ABSTRACT

Over the past several years a generic adaptive optics modeling capability has been developed at Raytheon Optical Systems Inc, and used in several projects for performance prediction. The model includes various details of an Adaptive Optics system servo loop built around a Hartman wavefront sensor, Reconstructor, Deformable Mirror and a Fast Steering Mirror for tilt control. The details include processing latencies, servo controller algorithm, atmospheric phase and intensity including scintillation effects, DM-WFS misregistrations, and pupil distortions. This model has been developed using Matlab, on the PC platform. The talk will give an overview of the model and its capabilities, including some of the results.

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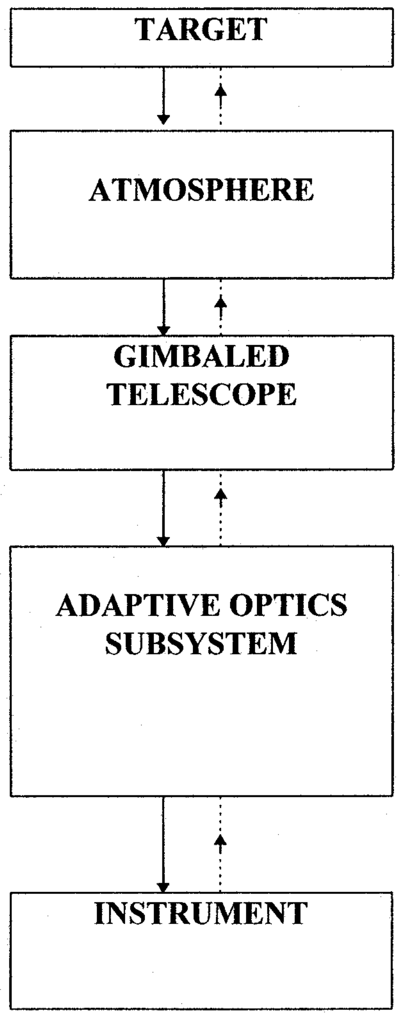
TYPICAL APPLICATION OF ADAPTIVE OPTICS FOR WAVEFRONT CORRECTION



- **The Target could be either a point target or an extended target, could be a star, satellite, artificial guide star, or missile, for example**

- **The Atmospheric Turbulence introduces time-varying wavefront (phase) errors, depending on (a) Wind (b) LOS Rate (c) Zenith Angle and (d) Other Weather Conditions.**
  The net result is represented by an index of refraction profile versus height called C_n^2 profile, and by layers of atmosphere moving at different velocities with respect to LOS. The severity of this is indicated by the following main parameters:
  (a) f_g , the Greenwood Frequency (temporal bandwidth of spatial orders higher than global tilt)
  (b) r_0 , the coherence length (spatial correlation of the disturbances)
  (c) σ_χ^2 , the log-amplitude variance (scintillation effects) and
  (d) f_t , the Tyler Frequency (temporal bandwidth of global tilt)

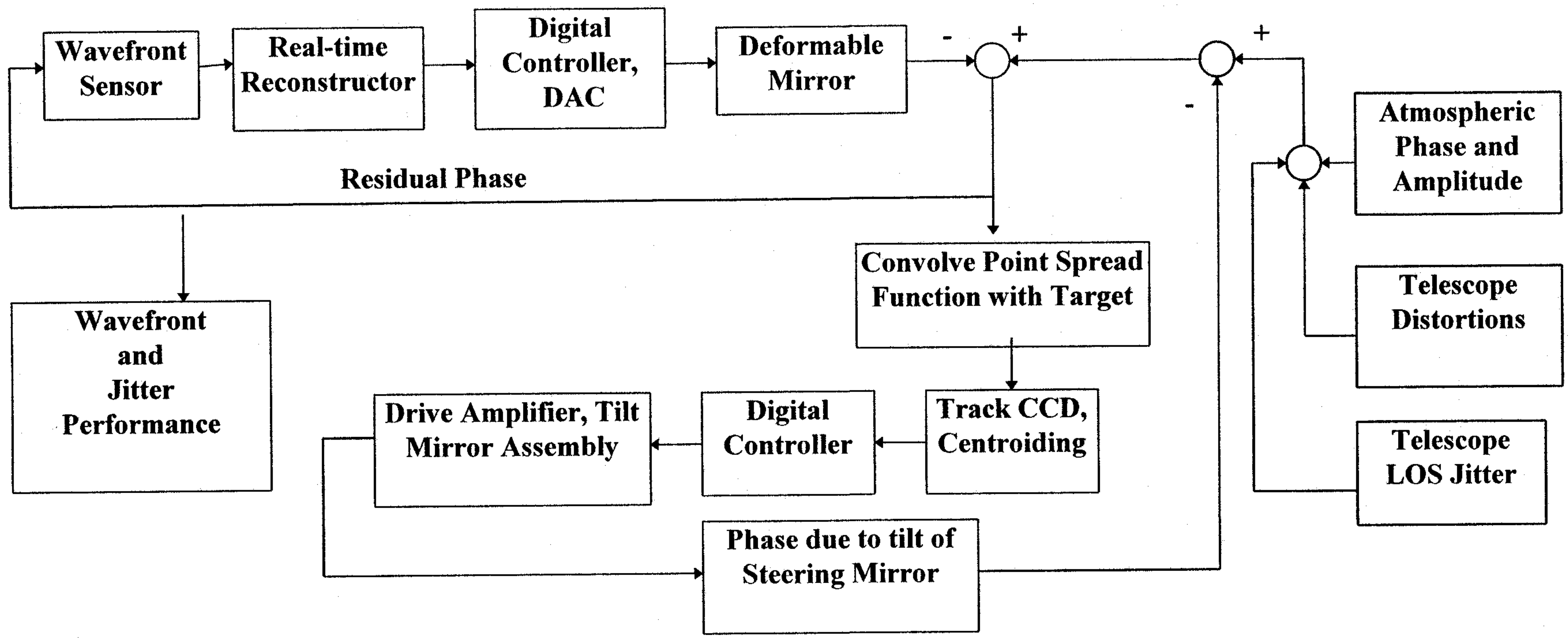
- **The Gimbaled Telescope introduces (a) LOS jitter, (b) some low frequency wavefront distortions and (c) some pupil wander**

- **The Adaptive Optics applies correction to the phase map over the pupil, such that the wavefront is of sufficient quality, either**
  (a) at the instrument as in the case of all imaging applications, for example,
  or (b) at the target as in the case of high energy delivery systems, for example

  This is typically accomplished by using the following components: (a) Wavefront Sensor, (b) Reconstructor, (c) Servo Controller, (d) Deformable Mirror, (e) Track Sensor and (f) Beam Steering Mirror.

- **Performance is typically characterized by metrics such as Strehl.**

TOP LEVEL ADAPTIVE OPTICS MODEL BLOCK DIAGRAM



THE FULL-UP TIME DOMAIN MODEL HAS DETAILS OF WAVEFRONT AND TILT CONTROL LOOPS NECESSARY TO ADDRESS ALL MAJOR PERFORMANCE AND DESIGN VERIFICATION ISSUES:

- o Misregistration betweenWavefront Sensor (WFS) and Deformable Mirror (DM)
- o Pupil Distortion of Optics between DM and WFS
- o Edge Effects and Slaving of actuators outside the illuminated area (pupil) of DM
- o Saturation non-linearities in WFS and DM drive; Quantization effects in RTR and Controller
- o Unobservable Modes (Waffle)
- o Accurate modeling of latencies (to microsecond accuracy)
  - o Dynamic effects of the servo-loop

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THE MODELING SOFTWARE TOOLS USED

- MATLAB Version 5

  For all time domain models, a suite of "m" files have been created as part of a GENERIC ADAPTIVE OPTICS model that are modular, performing various functions such as computing PSFs, OTFs, Centroiding, Registration, and for computing all the underlying modeling parameters based on the given input system geometry and system parameters.

  SIMULINK not used, for historical reasons and because of the very high dimensionality of the system and complexity of the operations involved.

- MathCAD

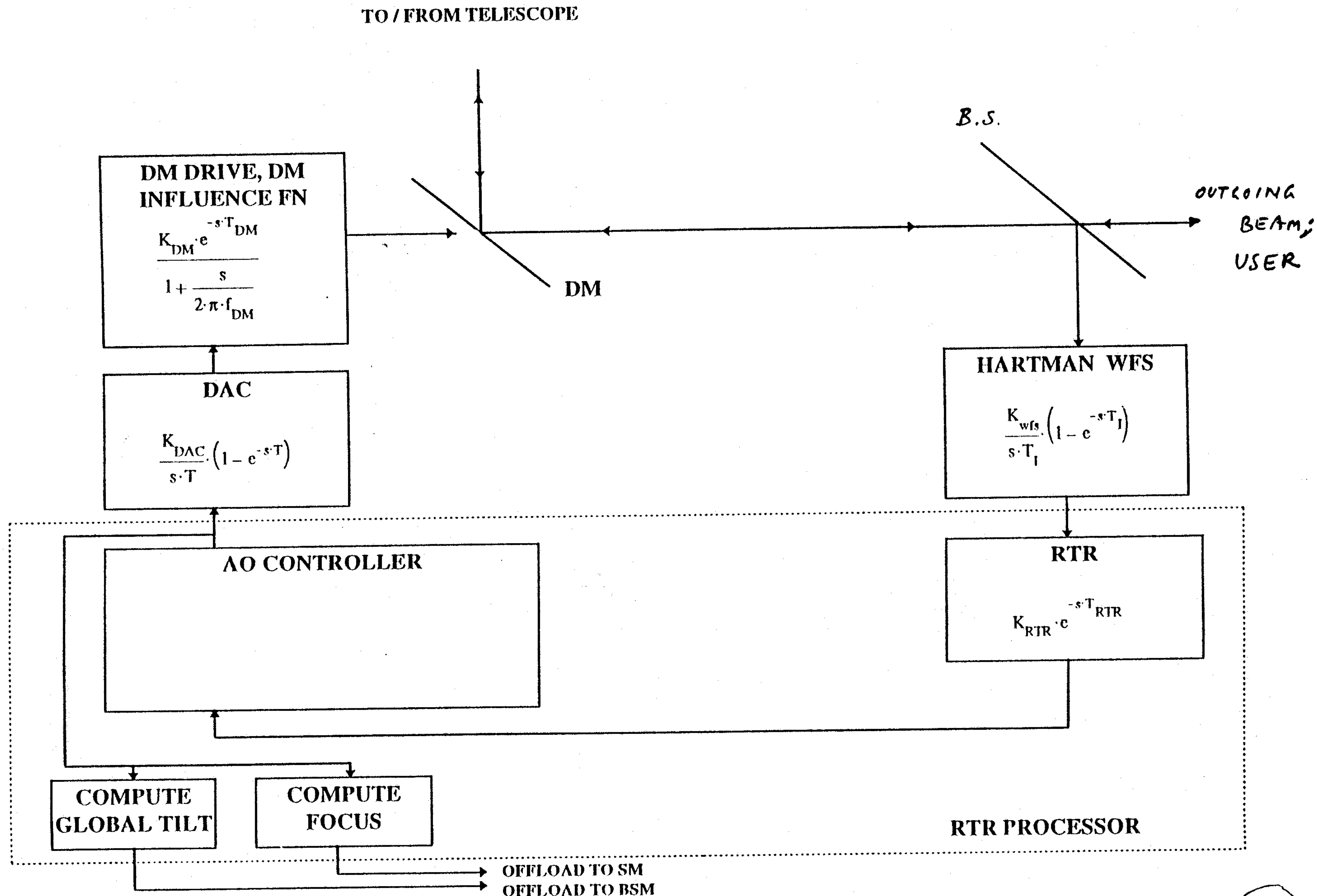
  For all frequency domain design of the servo loops. The controller parameters are then used in the time domain model.

- OPERATING SYSTEM: Windows NT

HARDWARE (current status)

Pentium II , 128 MB memory, 4 GB drive

HIGHER ORDER AO LOOP SIMPLIFIED BLOCK DIAGRAM



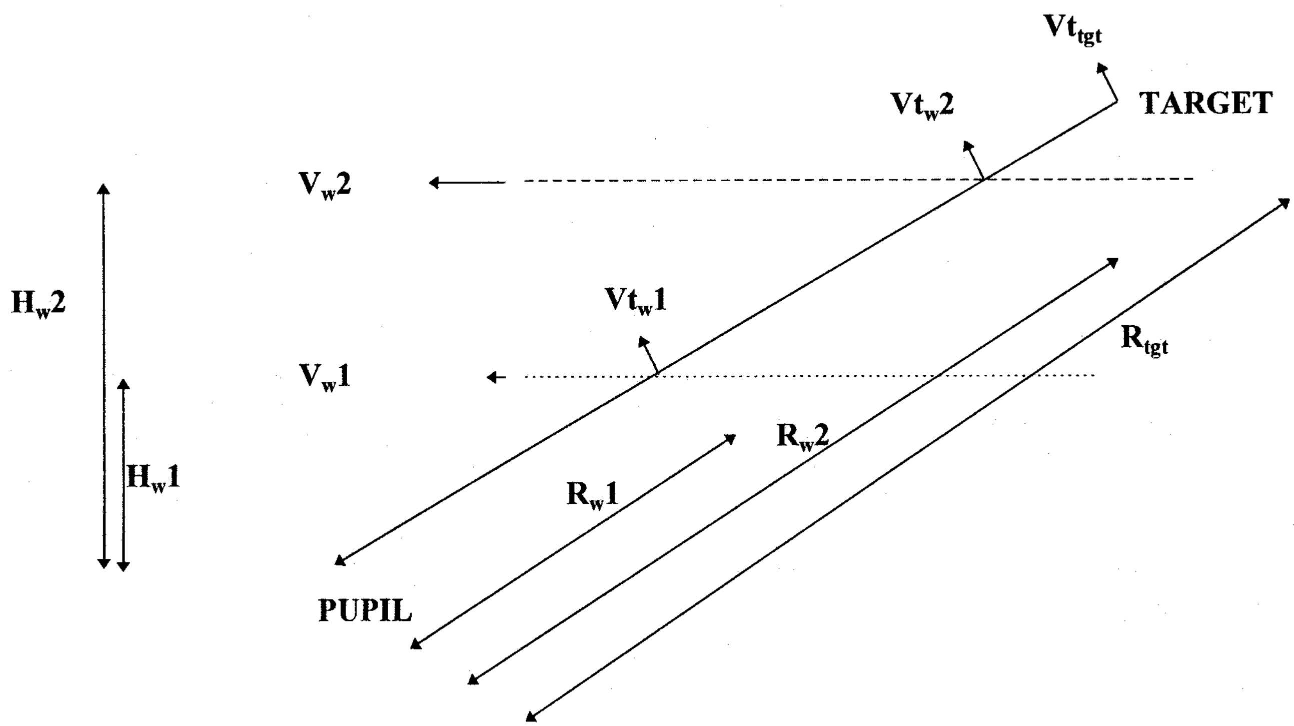
THE ATMOSPHERE

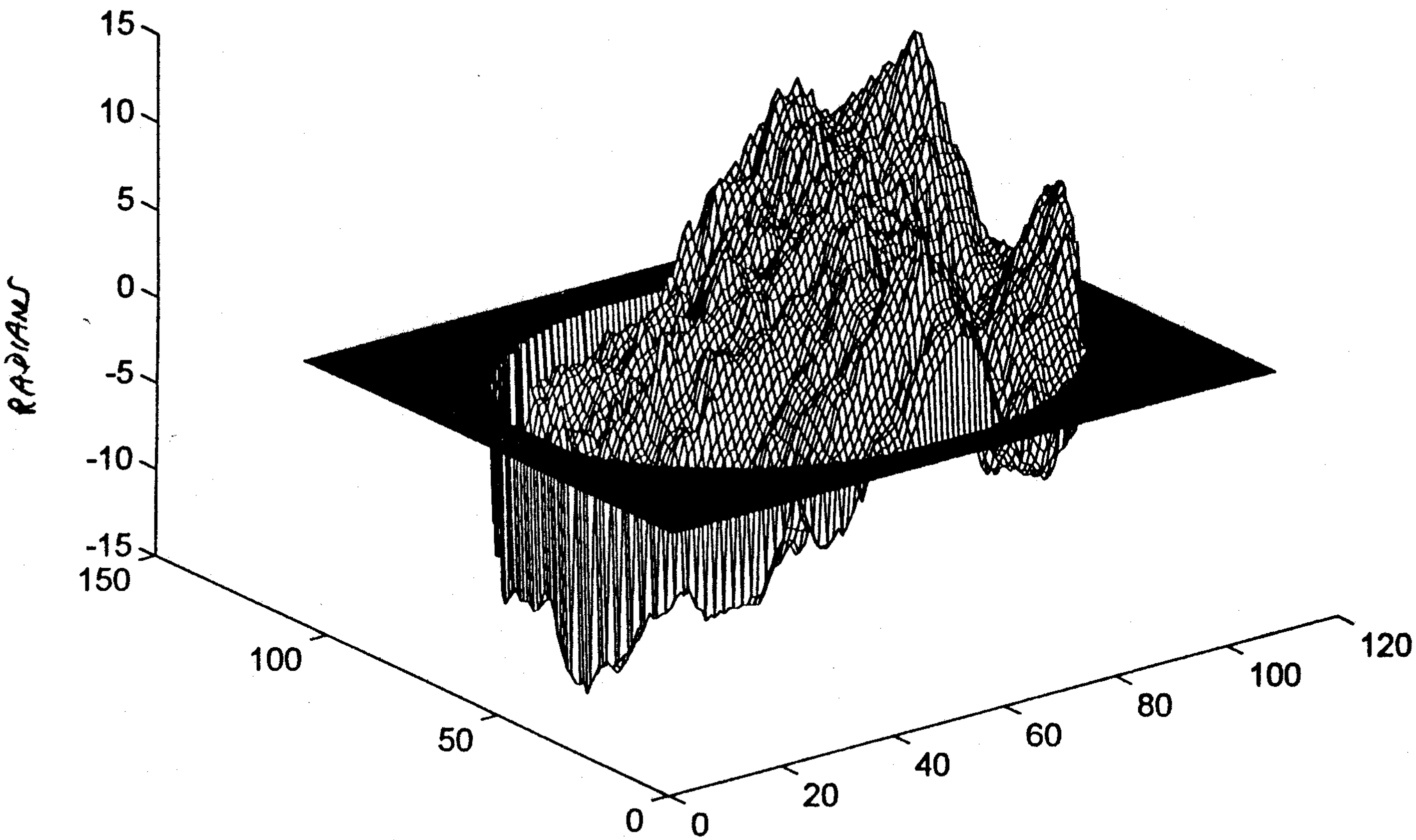
THE ATMOSPHERE IS MODELED BY GENERATING THE PHASE (AND AMPLITUDE) DATA SEPARATELY, AND USED AS INPUTS TO THE TIME_DOMAIN MODEL, IN ONE OF FOLLOWING WAYS:

(a) A SET OF PHASE SCREENS ARE MOVED ACROSS THE PUPIL AT APPROPRIATE VELOCITIES. TYPICALLY, ONLY ONE PHASE SCREEN IS USED.

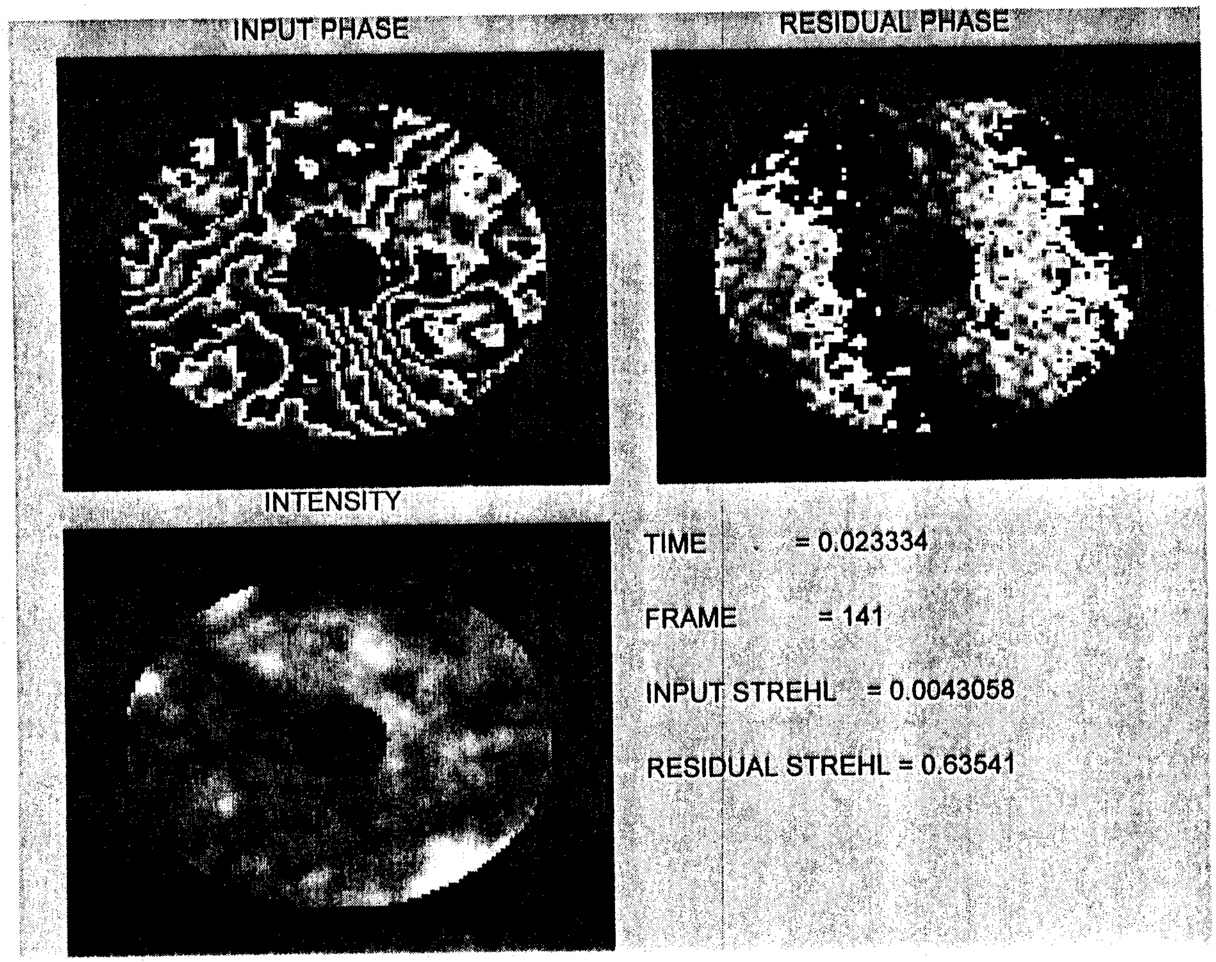
(b) ONE PHASE SCREEN AND ONE AMPLITUDE SCREEN ARE MOVED ACROSS THE PUPIL

(c) THE COMPLEX PHASE FUNCTION OVER THE PUPIL IS GENERATED OFFLINE FOR EVERY FRAME, AND USED (THIS IS THE MOST ACCURATE, WHEN SIGNIFICANT SCINTILLATION IS PRESENT)





15
10
5
0
-5
-10
-15
RADIANS
150
100
50
0
0
20
40
60
80
100
120


INPUT PHASE
RESIDUAL PHASE
INTENSITY
TIME = 0.023334
FRAME = 141
INPUT STREHL = 0.0043058
RESIDUAL STREHL = 0.63541

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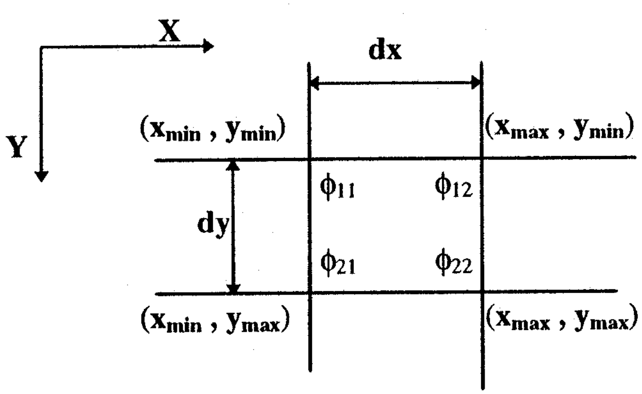
THE WFS MODEL

INPUT SLOPES COMPUTATION:

FOR A GIVEN OPD MAP Φ OF A WAVEFRONT (DEFINED ON THE FINE GRID) AT THE INPUT TO WFS, THE X AND Y SLOPES ARE COMPUTED FOR *EACH ILLUMINATED FINE GRID ELEMENT* AS FOLLOWS:



$$\text{Xslope} = (\phi_{12} - \phi_{11} + \phi_{22} - \phi_{21}) / (2dx)$$

$$\text{Yslope} = (\phi_{21} - \phi_{11} + \phi_{22} - \phi_{12}) / (2dy)$$

THEN THE INPUT SLOPE OF EACH ACTIVE SUBAPERTURE IS COMPUTED AS THE AVERAGE OF THE INPUT SLOPES OF ALL THE ILLUMINATED FINE GRID ELEMENTS WITHIN THAT SUBAPERTURE

IF Φ IS IN MICRONS, dx AND dy ARE IN MILLIMETERS, THEN THE SLOPES ARE IN MILLIRADIANS.

ϕ_{11}, ϕ_{12}, ϕ_{21}, ϕ_{22} ARE VALUES AT THE CORNERS, INTERPOLATED FROM THE WAVEFRONT LEAVING THE DM, TAKING INTO ACCOUNT THE MISREGISTRATIONS AND PUPIL DISTORTION

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THE WFS MODEL(Contd)

SUBAPERTURE INTENSITIES:

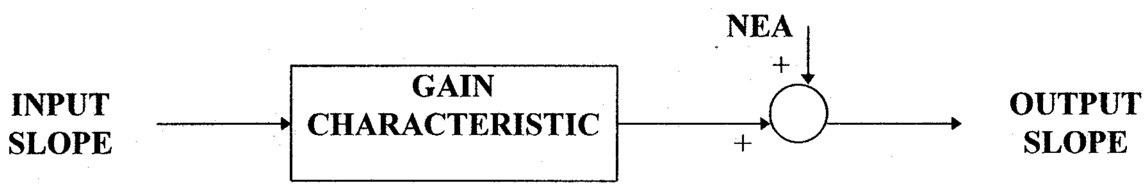
THE INTENSITY IN EACH ACTIVE SUBAPERTURE IS PROPORTIONAL TO THE NUMBER OF ILLUMINATED FINE GRID ELEMENTS IN THAT SUBAPERTURE.
THESE ARE WEIGHTED WITH THE INTENSITY MAP CAUSED BY SCINTILLATION EFFECTS

OUTPUT SLOPES:

THE WFS IS MODELED AS A SET OF NON-LINEAR GAIN CHARACTERISTICS, AND AN ADDITIVE NOISE EQUIVALENT INPUT. THESE TARGET SIZE DEPENDENT GAIN CHARACTERISTICS AND THE NEA VALUES USED IN THE MODEL ARE GENERATED BY DETAILED SUBSYSTEM ANALYSIS

THE NOISE EQUIVALENT INPUT FOR EACH SUBAPERTURE DEPENDS ON THE INTENSITY IN THAT SUBAPERTURE

THE OUTPUT SLOPES ARE IN THE SAME UNITS AS THE INPUT SLOPES.



THE WAVE PROPAGATION MODEL OF WFS IS UNDER DEVELOPMENT

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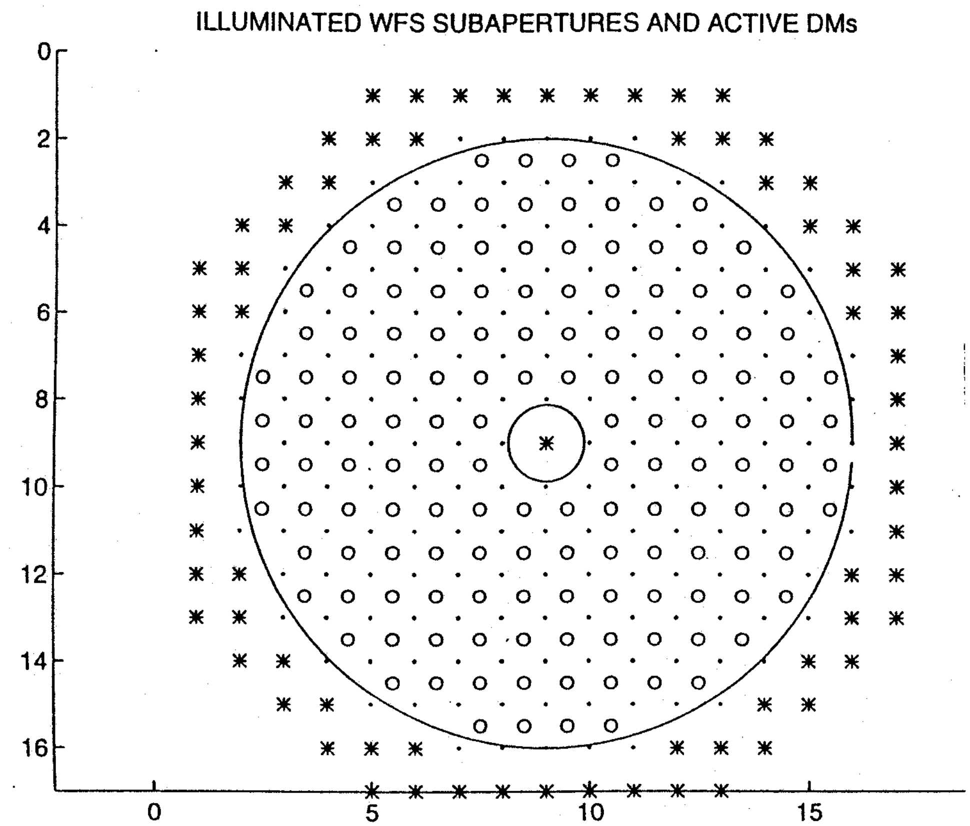
THE RECONSTRUCTOR

o **THE GEOMETRY:**

THE FIRST STEP IS TO DEFINE THE FOLLOWING, ON WHICH THE RECONSTRUCTOR DEPENDS:
(a) THE DM ACTUATOR POSITIONS IN RELATION TO THE ILLUMINATED APERTURE
(b) THE INDEPENDENT AND "SLAVE" ACTUATORS, AND THE SLAVING FORMULA (eg NEAREST NEIGHBOUR)
(c) THE ACTIVE WFS SUBAPERTURES



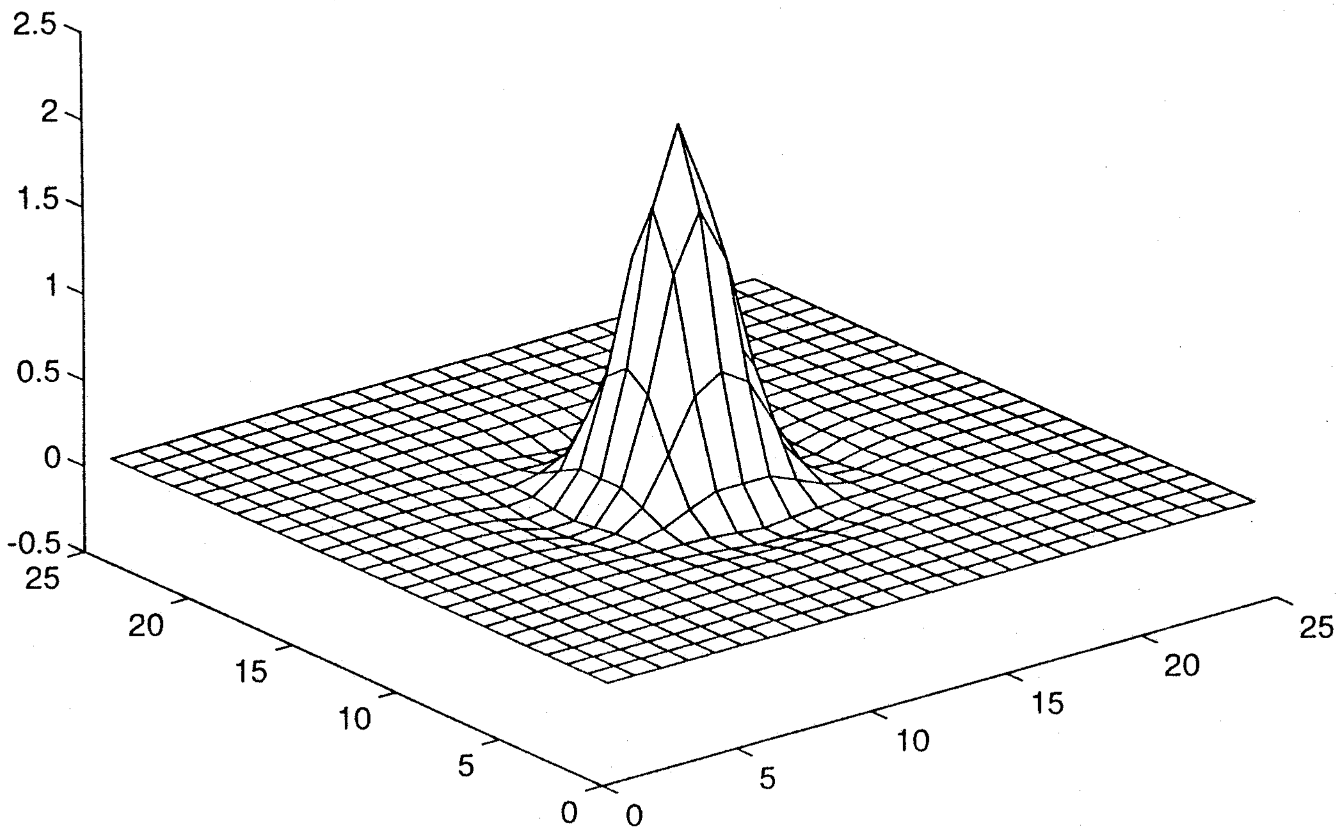
17 x17 grid. for DM Actuators.

$\text{Dm spacing} = \frac{26\text{ cm}}{14} = 18.571\text{ mm}$ ← 14 x 14 grid for Wavefront sensor subapertures.

o : Active WFS subaperture
• : Active Independent DM actuator
* : Active Slave DM. actuator

Number of active WFS subapertures = 144 (slopes = 288)
Number of active independent DM actuators = 176
Number of active slave DM actuators = 73
Total DM actuat[ors] = 249

DM INFLUENCE FUNCTION ON FINE GRID (3 FINE GRID SPACES PER ACTUATOR SPACING)



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THE RECONSTRUCTOR(Contd)

THE SENSITIVITY MATRIX:

THE WFS OUTPUT SLOPES ARE COMPUTED FOR EACH INDEPENDENT ACTUATOR, TAKING INTO ACCOUNT THE SLAVE ACTUATOR(S) THAT MAY DEPEND ON THAT INDEPENDENT ACTUATOR, AND ASSUMING A NOMINAL LINEAR WFS GAIN.

LET $\underline{dmi}$ = VECTOR OF INDEPENDENT DM ACTUATOR MOTIONS, SIZE (Nind,1)
$\underline{dms}$ = VECTOR OF SLAVE DM ACTUATOR MOTIONS, SIZE (Nslave,1),
= SLAVE * $\underline{dmi}$, SIZE OF SLAVE = (Nslave, Nind),
$\underline{dm}$ = [$\underline{dmi}$
$\underline{dms}$] = VECTOR OF ALL DM ACTUATOR MOTIONS, SIZE (Ndmv, 1),
Ndmv = Nind + Nslave
$\underline{slp}$ = VECTOR OF WFS OUTPUT SLOPES, SIZE (2*Nsubap,1),
Nsubap = NUMBER OF ACTIVE SUBAPERTURES,
TYPICALLY 2*Nsubap > Nind

THEN, FROM THE ABOVE SENSITIVITY COMPUTATIONS, WE GET THE SENSITIVITY MATRIX SENS,

$$\boxed{\begin{array}{c} \underline{slp} = SENS * \underline{dmi} + \underline{noise} \\ \text{with} \\ \underline{dms} = SLAVE * \underline{dmi} \end{array}}$$

WHERE $\underline{noise}$ IS MEASUREMENT NOISE, AND SIZE OF SENS = (2*Nsubap, Nind)

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THE RECONSTRUCTOR(Contd)

THE RECONSTRUCTION MATRIX:

FROM THE LEAST SQUARES RECONSTRUCTOR DISCUSSED EARLIER, WE HAVE

dmiLS = InvSENS * slp , WITH dms = SLAVE * dmiLS , WHERE InvSENS IS PinvSENS WITH PISTON AND WAFFLE REMOVED, AND SO THE TOTAL DM ACTUATOR VECTOR dmLS IS GIVEN BY

dmLS = [dmiLS
SLAVE * dmiLS]
= [InvSENS
SLAVE * InvSENS] * slp

THAT IS,

$$\boxed{\underline{\mathrm{dmLS}} = \mathrm{RTR} * \underline{\mathrm{slp}}}$$

WHERE RTR = [InvSENS
SLAVE * InvSENS] IS THE RECONSTRUCTION MATRIX

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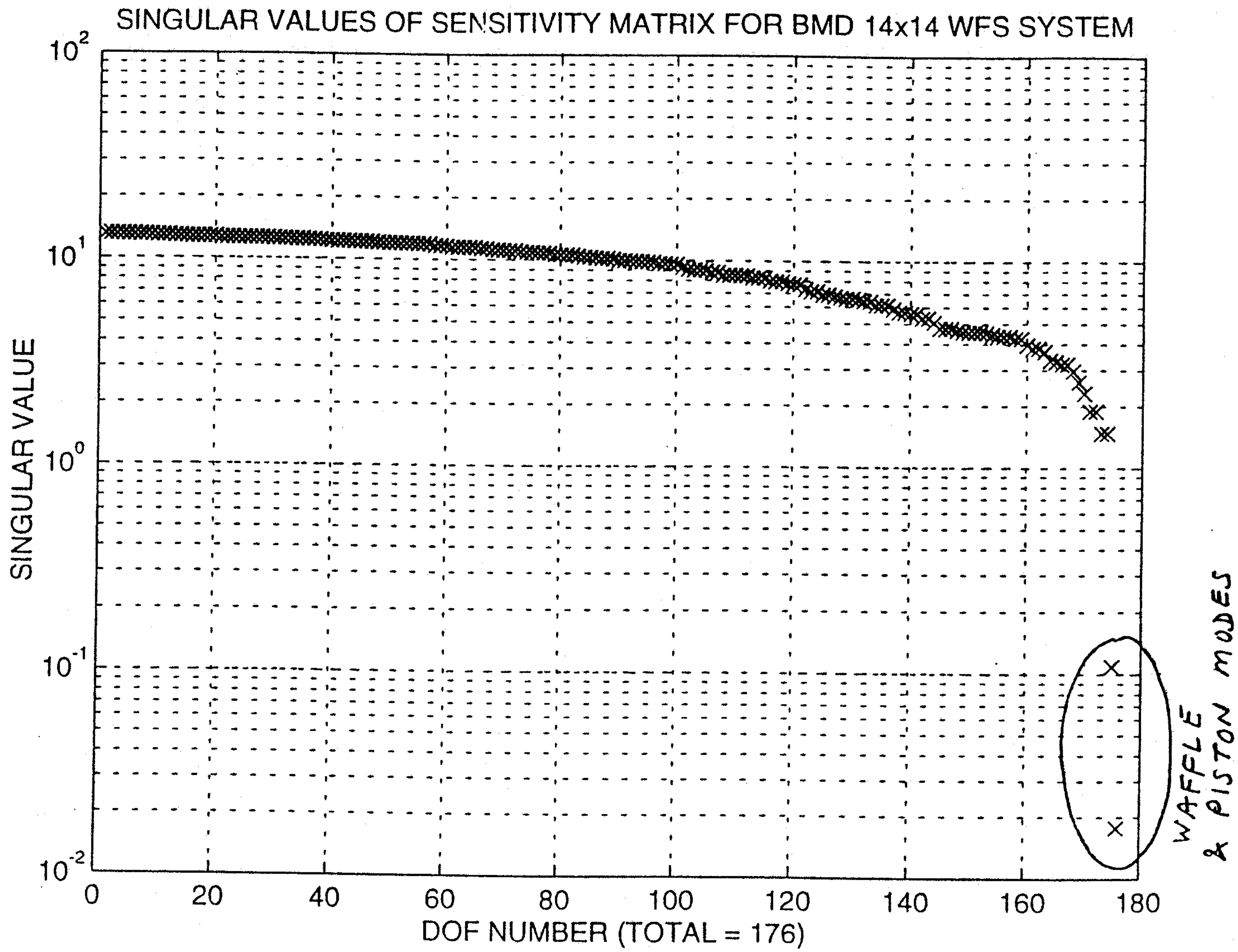

FIGURE 3.

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SUM OF 176th AND 175th SINGULAR VALUE DM MODES (WAFFLE)

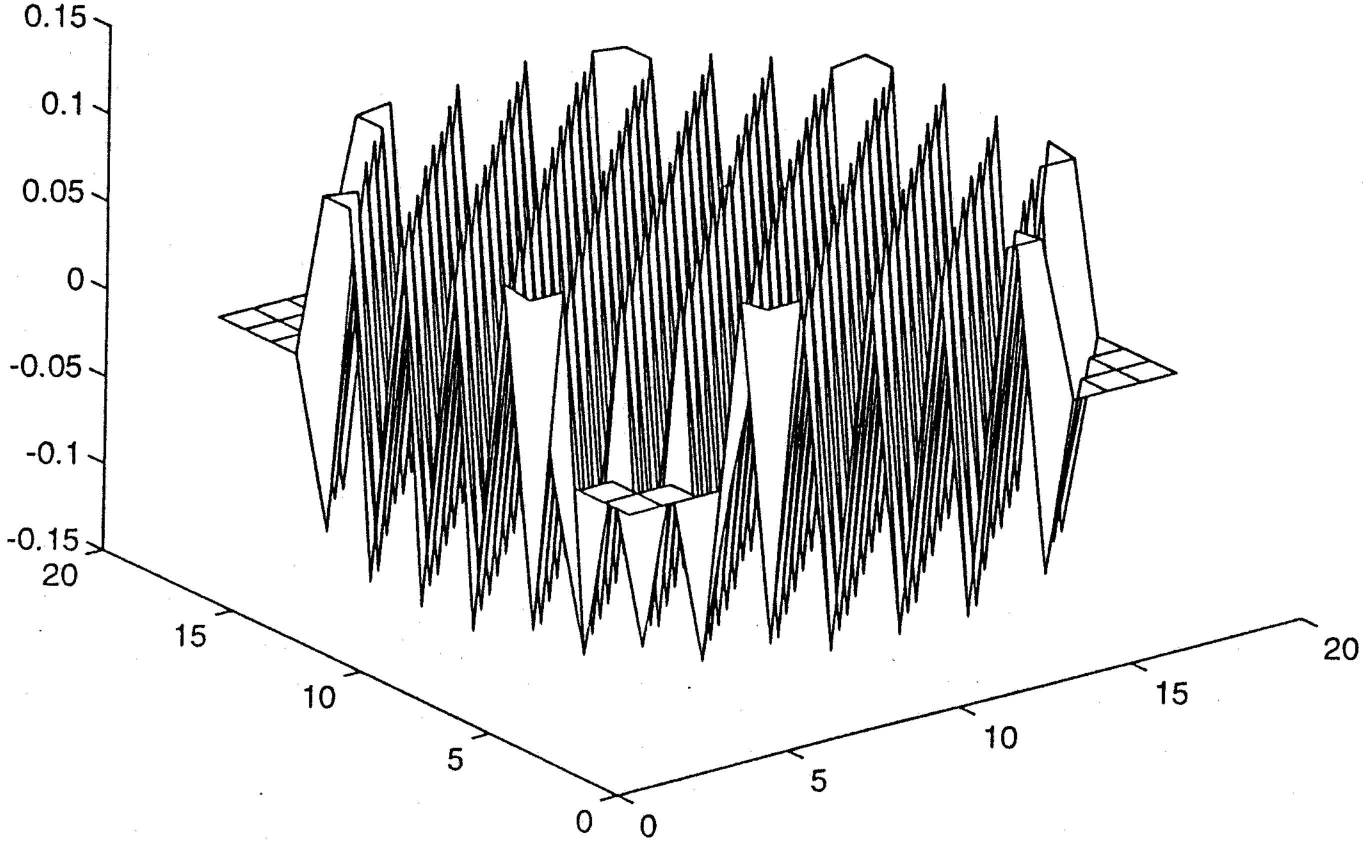

FIGURE 4(a)

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DIFFERENCE OF 176th AND 175th SINGULAR VALUE DM MODES (PISTON)

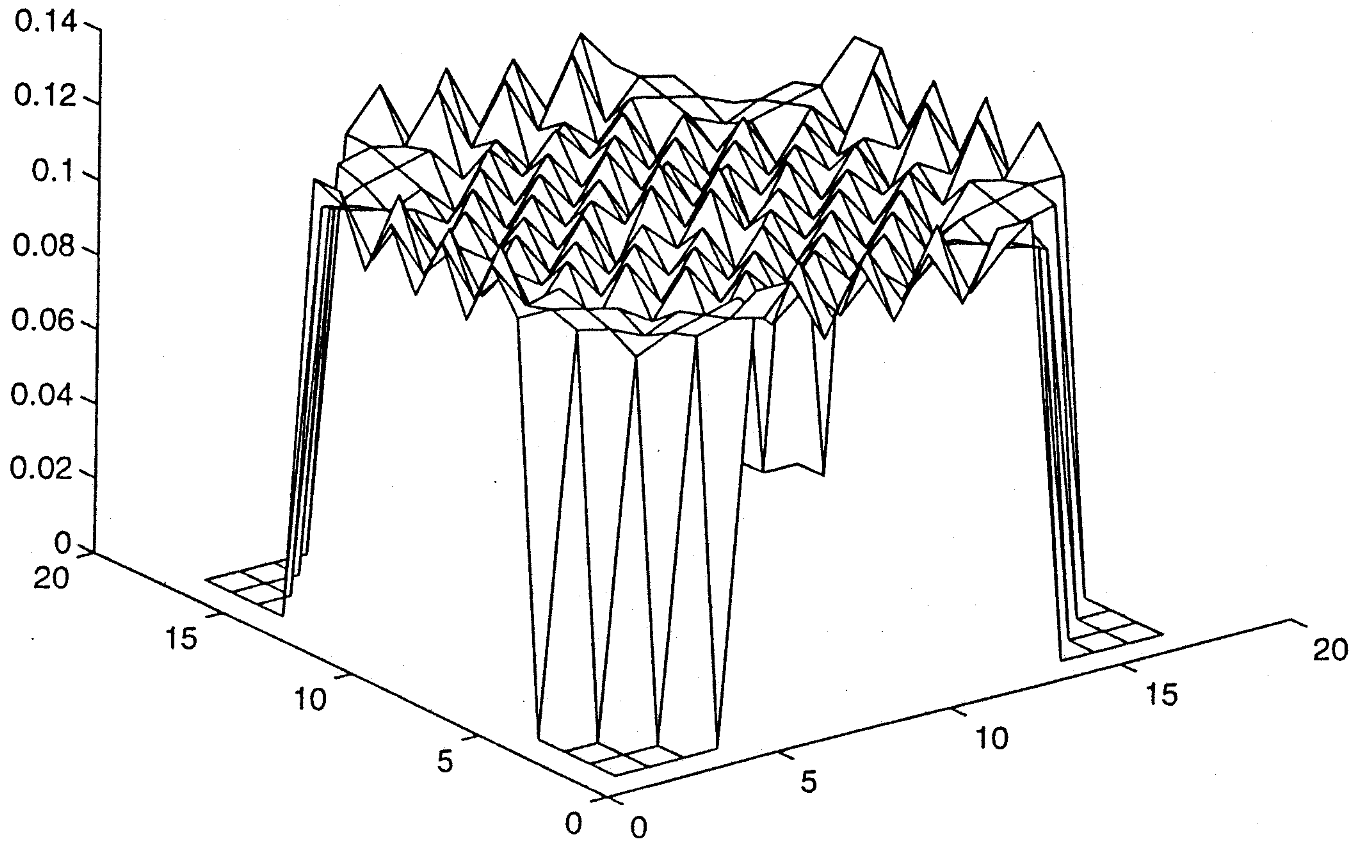

FIGURE 5

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» simp107
WELCOME TO THE HDOS GENERIC ADAPTIVE OPTICS MODEL

ENTER THE TWO CHARACTER RUN ID, ENCLOSED IN SINGLE QUOTES
CAUTION: THE DISC FILES WITH THE RUN ID WILL BE OVERWRITTEN

>'ye'
ID= 1:TRK BW ID(int):1=300;2=200;3=100;4=75;5=50;6=25;7=10 Hz=          1
ID= 2:WF BW ID(int):1=100;2=200;3=350;4=500;5=550;6=600       =          5
ID= 3:NO ATMOSPHERICS FLAG: (1=NO ATMOSPHERICS)               =          0
ID= 4:NO WFS NOISE FLAG: (1=NO WFS NOISE)                     =          0
ID= 5:NO TRACK SENSOR NOISE FLAG:(1=NO TRACK SENSOR NOISE)    =          1
ID= 6:RUN LENGTH (NUMBER OF WFS FRAMES,integer)               =        140
ID= 7:R0  (METERS)                                            =     0.0300
ID= 8:LOS RATE (RADIANS/SEC)                                  =     0.0013
ID= 9:ALTITUDE OF (SINGLE LAYER) PHASE SCREEN (METERS)        =10000.0000
ID=10:WFS SNR                                                 =    10.0000
ID=11:TELESCOPE JITTER (OBJECT SPACE, MICRORADIANS RMS)       =     0.0000
ID=12:TARGET SIZE (OBJET SPACE, MICRORADIANS)                 =     0.0000
ID=13:TRACK SENSOR WAVELENGTH (MICRONS)                       =     1.5000
ID=14:WFS WAVELENGTH (MICRONS)                                =     1.5000
ID=15:SCORING WAVELENGTH (MICRONS)                            =     1.5000
ID=16:PHASE SCREEN WAVELENGTH (MICRONS)                       =     1.0000
ID=17:WFS SATURATION LEVEL (mRAD TILT, WFS INPUT SPACE)       =    50.0000
ID=18:DM-WFS X-MISREGISTRATION (mm)                           =     0.0000
ID=19:DM-WFS Y-MISREGISTRATION (mm)                           =     0.0000
ID=20:DM-WFS CLOCKING (degrees)                               =     0.0000
ID=21:PUPIL DISTORTION MAP SCALE (1.0=NOMINAL VALUE)          =     0.0000
ID=22:TELESCOPE DISTORTION SCALE (1.0=NOMINAL  TELESCOPE)     =     1.0000
ID=23:TILT LOOP GAIN (1.0= NOMINAL; 0.0= FREEZE TILT MIRROR)  =     0.1000
ID=24:WFS X-GAIN / WFS Y-GAIN (1.0 = NOMINAL)                 =     1.0000
ID=25:CASE # (                                              ) =          1
ID=26:SCINTILLATION FLAG (0=OFF; 1=ON)                        =          1
ID=27:WEIGHTING FLAG: (0=OFF; 1=ON)                           =          1
ID=28:WEIGHTING THERSHOLD, NORMALIZED TO AVERAGE INTENSITY    =     1.0000
ID=29:WEIGHTING MAX LEFT SHIFTS ( 0 = FULL PRECISION)         =          8
ID=30:SINUSOID FLAG (0=OFF; 1=ON)                             =          0
ID=31:SINUSOID FREQUENCY (Hz)                                 =   330.0000
ID=32:DIFFERENTIAL STROKE (MICRONS,TOTAL; -VE =NO LIMIT)      =     3.0000
ID=33:ATMOSPHERIC MODEL(1=tOSC; 2=HDOS PHMAP; 3=CMPLX SCRNS)  =          3
Loading Data Files and Initializing; Please Wait ...
```

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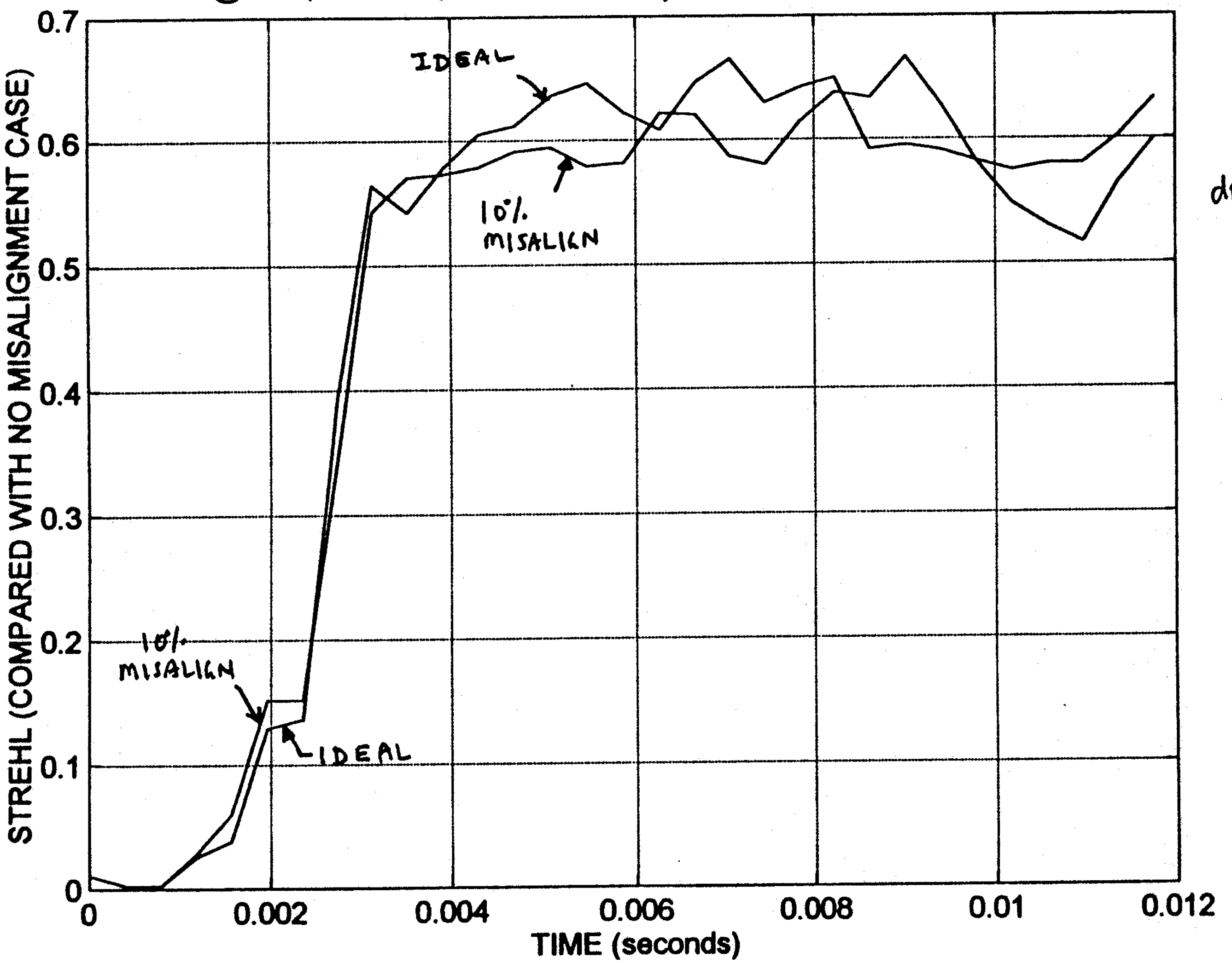
d1: r0=0.113 @ 0.65; BW=200; v=32m/s; Mv=4.~~2~~5; Y-MISALIGN=10% SUBAP; RTR=IDEAL



d1 : mean over 0.08 sec
= 0.59

FIGURE 2

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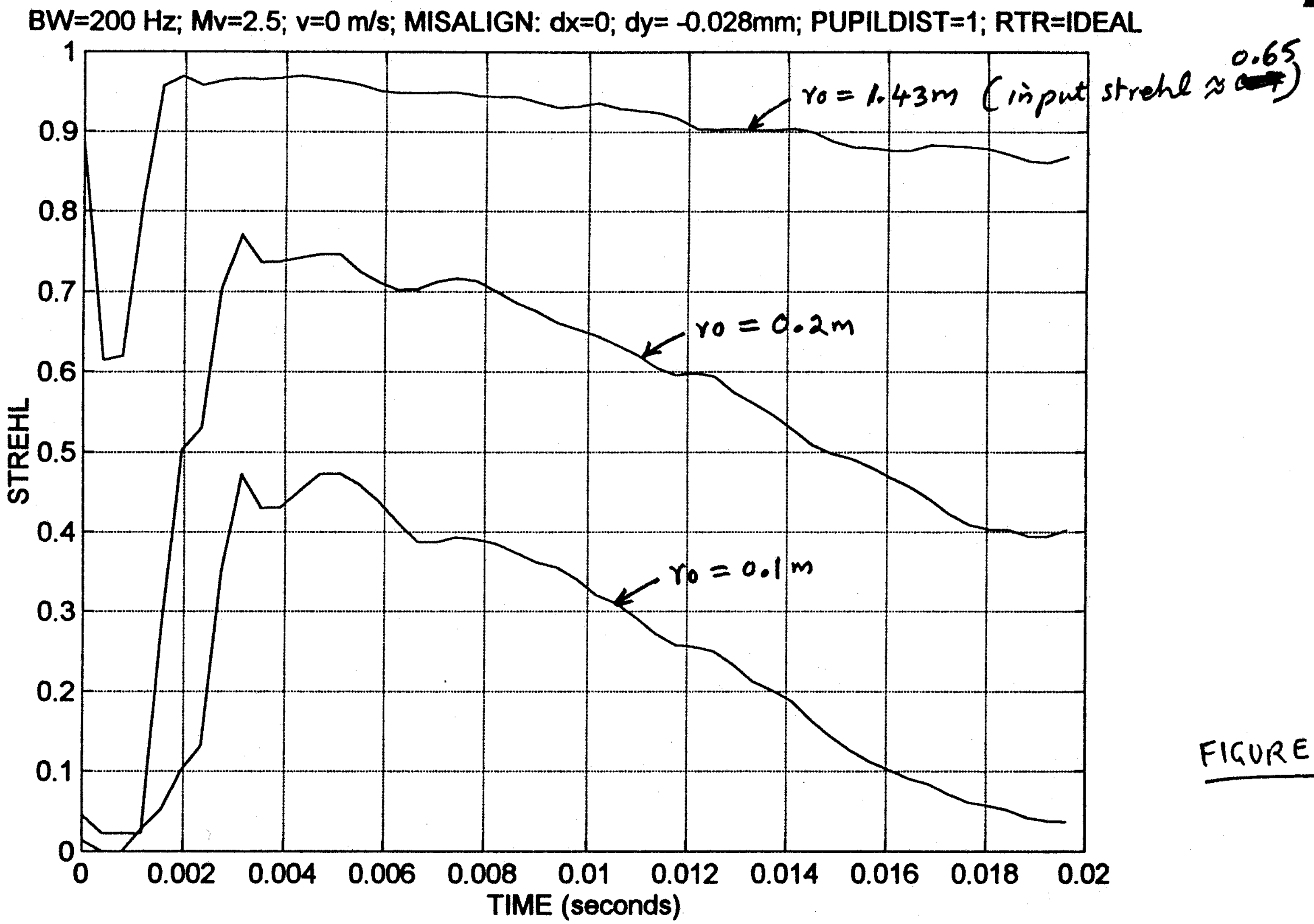

FIGURE 1

MISREGISTRATION = 33% OF SUBAPERTURE.

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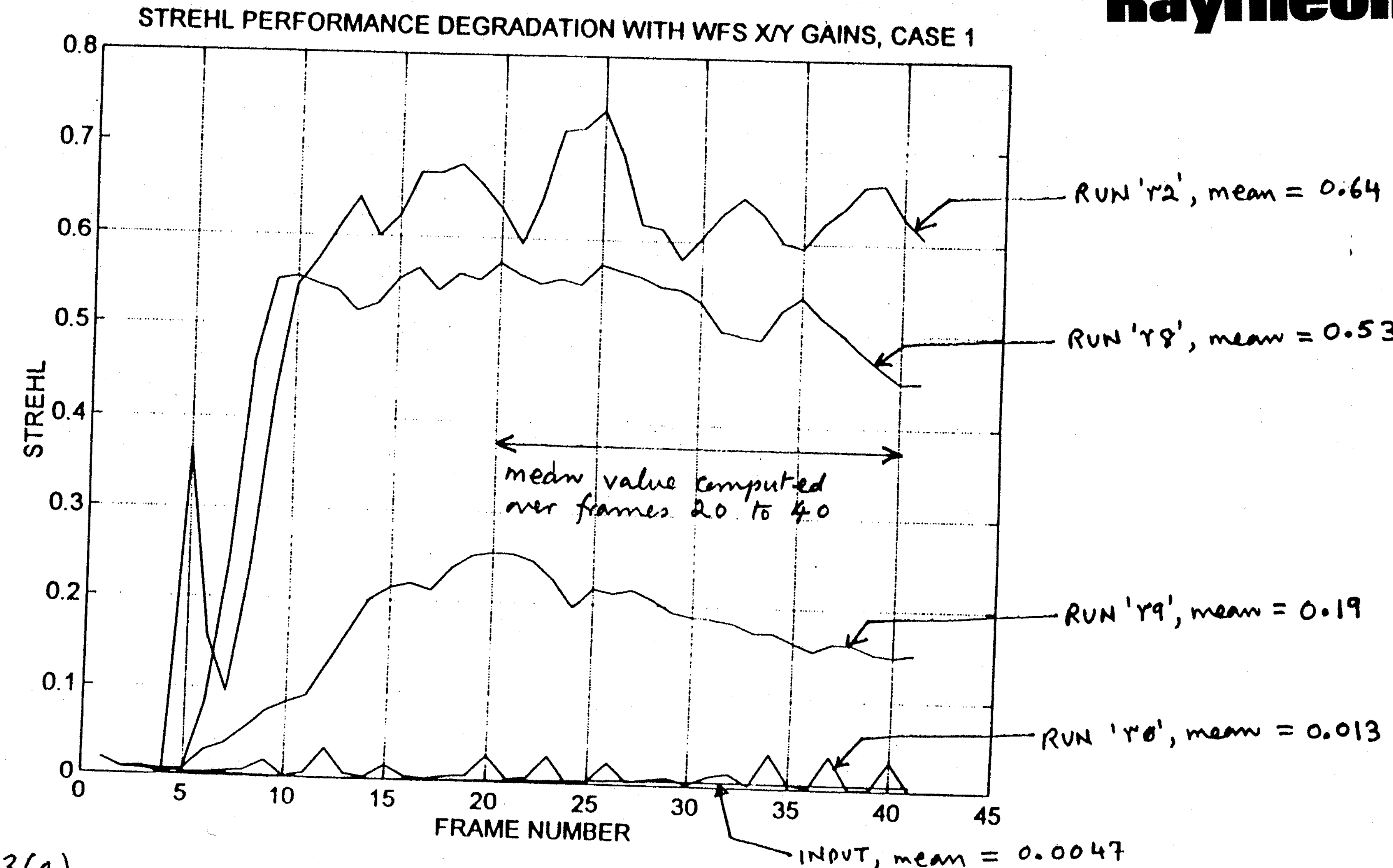


FIGURE 3(a)

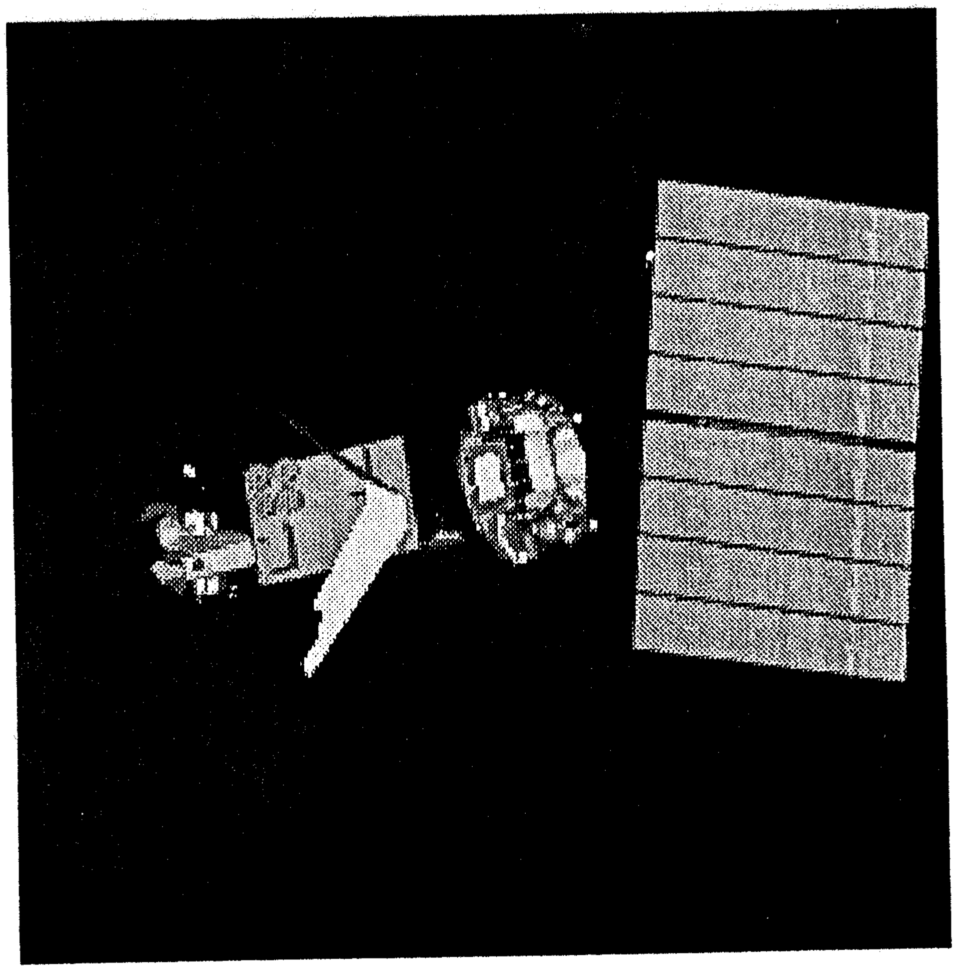
CASE 1

GREENWOOD FREQUENCY = 78 Hz
AO SERVO BW = 150 Hz
R_0 = 0.16 meters.
M_v = 5.0

NOTE: For all the runs, the Y-axis gain is set to the nominal value.

	CASE 1				CASE 2	
Run ID	'r2'	'r8'	'r0'	'r9'	'r3'	'ra'
XGain/YGain	1.0	0.333	3.0	0.10	1.0	0.333
STREHL	0.64	0.53	0.013	0.19	0.28	0.053
RESIDUAL WF RMS (Radians)	0.69	0.81	2.57	1.29	1.22	1.74

OBJECT



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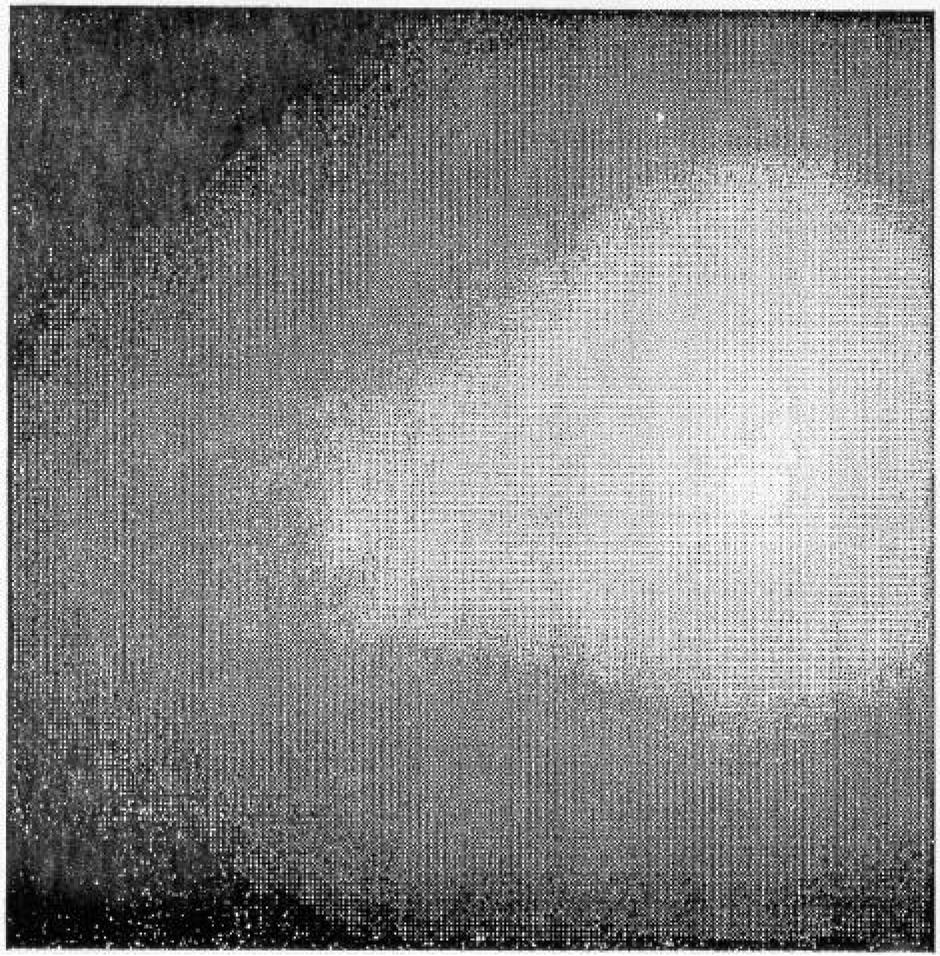
UNCORRECTED, TILT REMOVED IMAGE; PSF STREHL = 0.006



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AO CORRECTED IMAGE; PSF STREHL = 0.11

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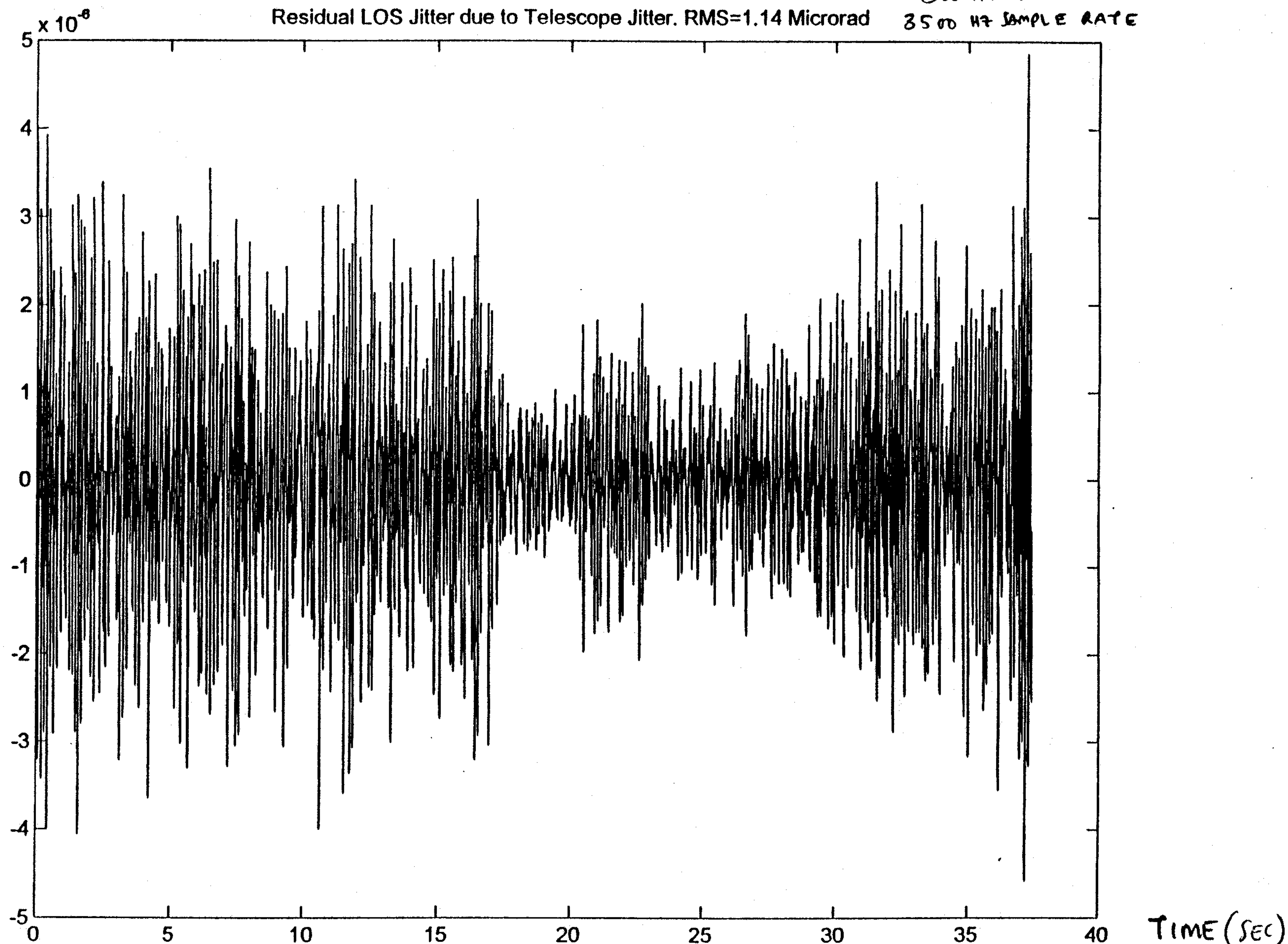
BASELINE CASE

11/12/94
300 HZ BW
3500 HZ SAMPLE RATE



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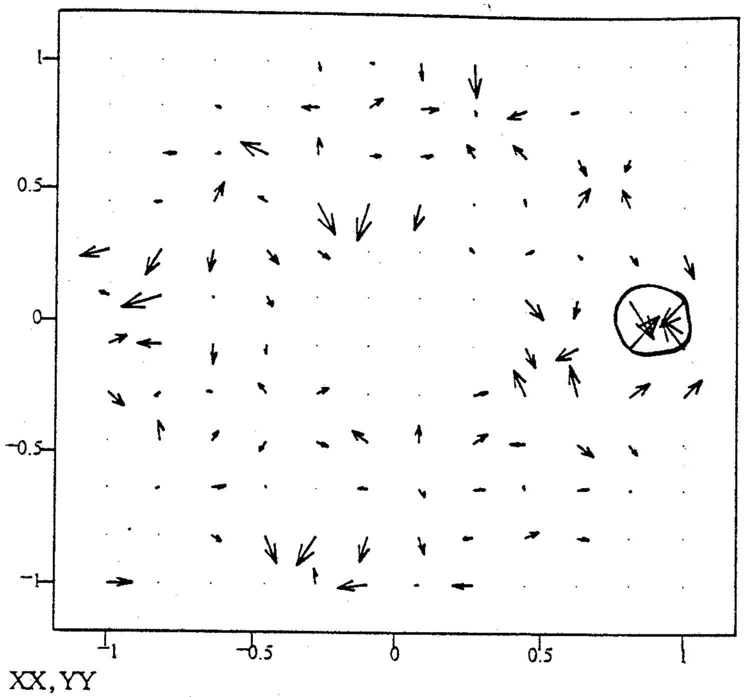
Run of Mar20, Iteration number 0 This is plot of DM on vs DM off before flattening



Set a reference vector for vector plot

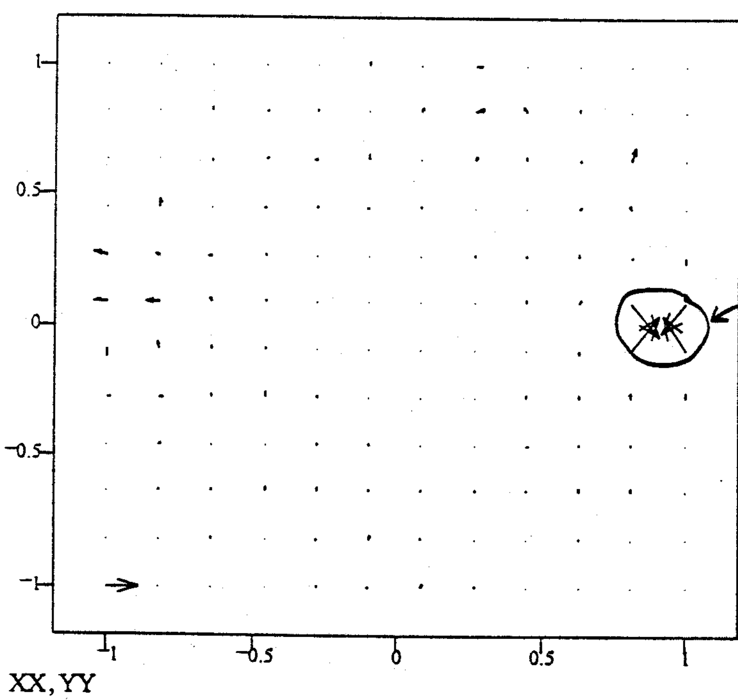
X-offset in pixels:

$\delta x = 0.002$ (elevation)

Y-offset in pixels:

$\delta y = -0.092$ (azimuth)

Run of Mar20, Iteration number 3 in closed loop process of flattening DM



Set a reference vector for vector plot

X-offset in pixels:

$\delta x = -0.002$ (elevation)

Anamolous area on DM.

Y-offset in pixels:

$\delta y = 0.08$ (azimuth)

MEASURED DATA, SHOWING CONVERGENCE